DESIGN OF ROTORS FOR IMPROVED STRUCTURAL LIFE

J. T. Hill

Pratt & Whitney Aircraft Group
Commercial Products Division
United Technologies

ABSTRACT

Failure of any large portion of a jet engine rotor structure poses a threat of uncontained case penetration; therefore, considerable care and study is directed to the design, analysis, manufacture and inspection of these components to ensure that rotor failure is avoided over the full life of the engine. In this presentation, major rotor design criteria will be discussed with particular emphasis on those aspects of rotor design that ensure long life component integrity. Included will be a review of dynamic considerations, that necessitate tuning of bladed disk and seal assemblies to avoid excessive vibratory stress at both design and off-design conditions; and low cycle fatigue considerations, which have resulted in detailed analysis procedures to establish part temperature and stress variation throughout an operating cycle and extensive specimen and component fatigue testing to establish safe cyclic operating limits. Undetected, subsurface flaws can cyclically grow to failure if smooth section stresses are not restricted; therefore, investigations to characterize the frequency, size and behavior of intrinsic material defects have been implemented and results will be reviewed.

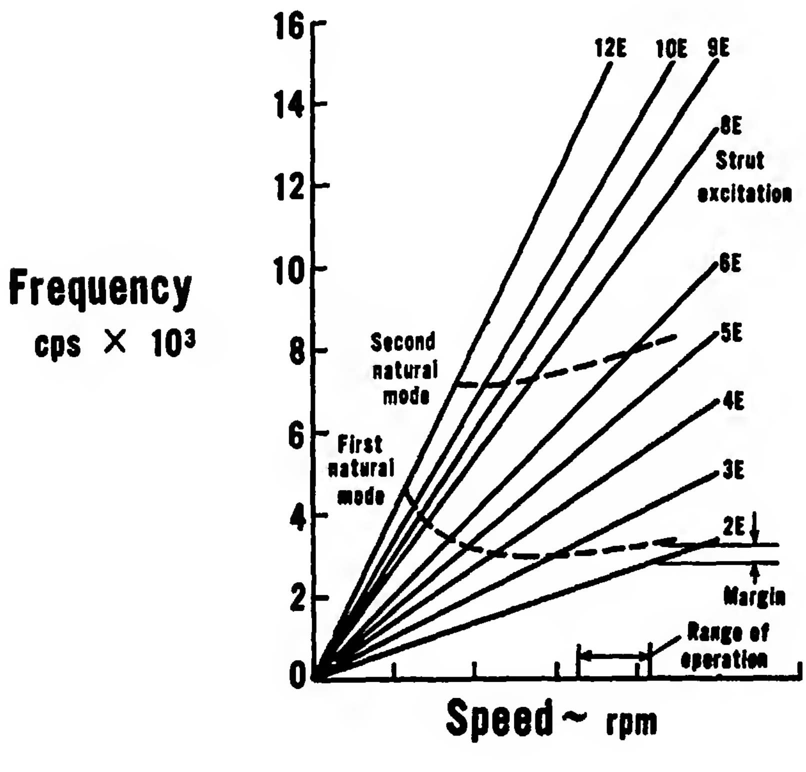
Manufacturing process improvements, including the application of increasingly sophisticated inspection techniques and quality control procedures will be reviewed in light of their impact on component durability.

UNCONTAINED DISK AND SEAL FAILURES

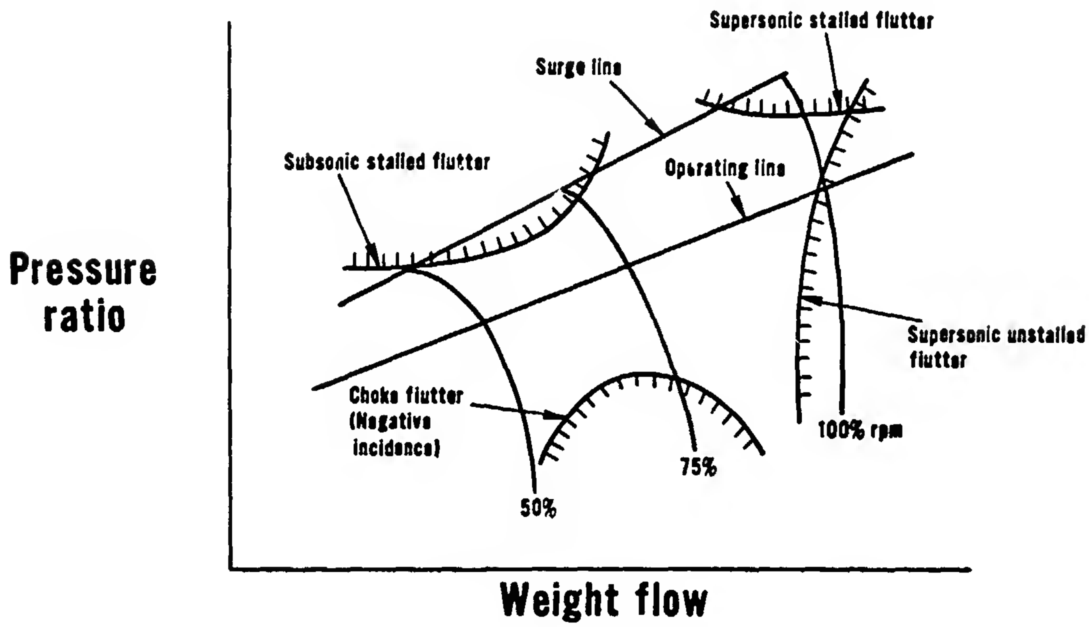
Major causes

- High cycle fatigue
- Material or manufacturing defects
- Low cycle fatigue

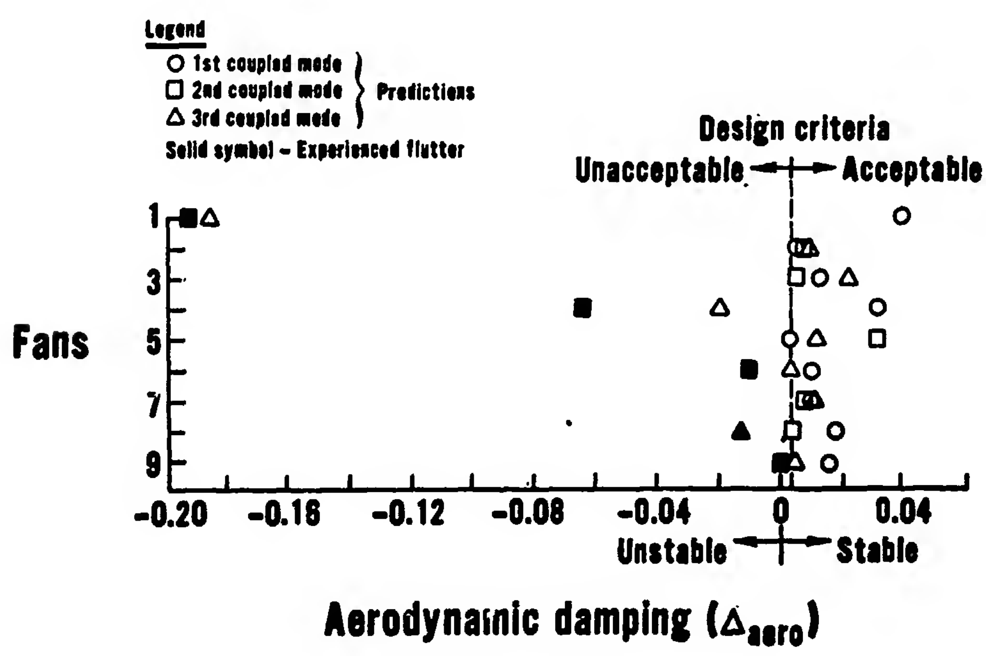
STAGE RESONANCE DIAGRAM



FLUTTER BOUNDARIES FOR FOUR FLUTTER TYPES



SUPERSONIC UNSTALLED FLUTTER ANALYSIS - CORRELATION

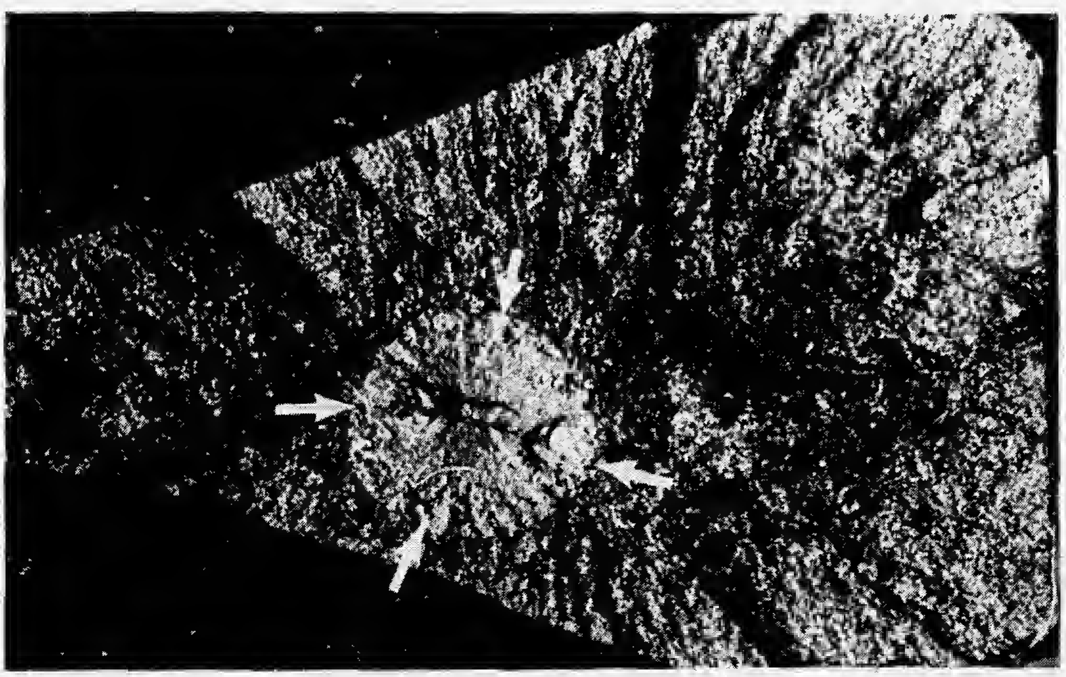


HIGH FREQUENCY FATIGUE

Summary

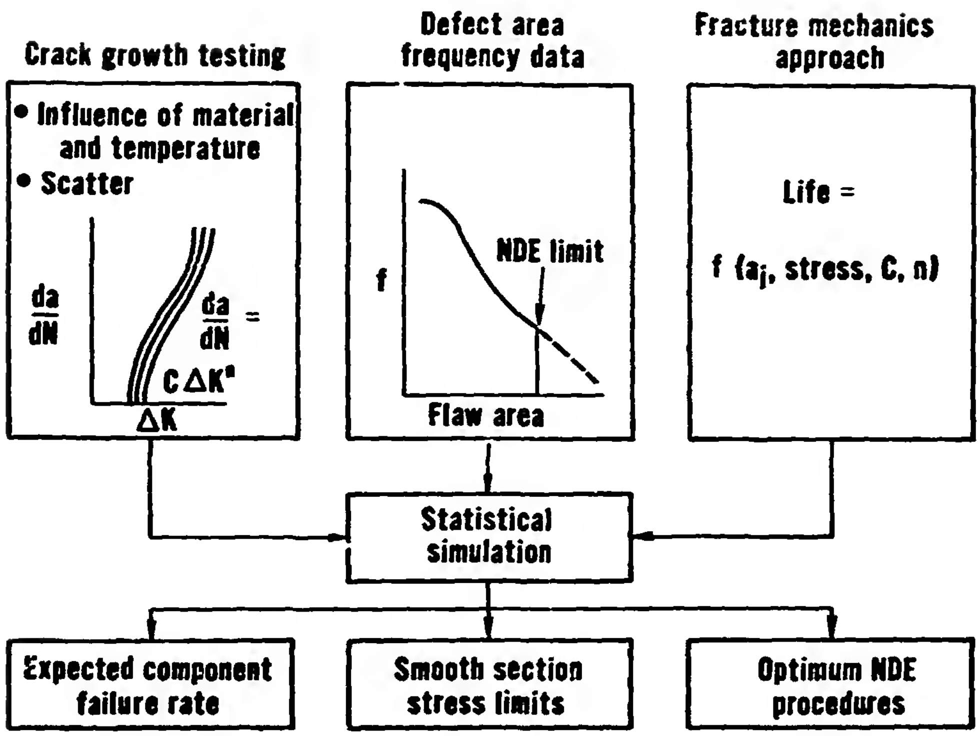
- Rotor resonance frequencies predictable
- Analytical systems exist to predict flutter in rotor components
- Engine development programs minimize vibratory problems
- Advanced analytical systems in development
  - Stalled and unstalled flutter predictions
  - Airfoil resonant stress predictions

FRACTURE ORIGINATING FROM MATERIAL DEFECT

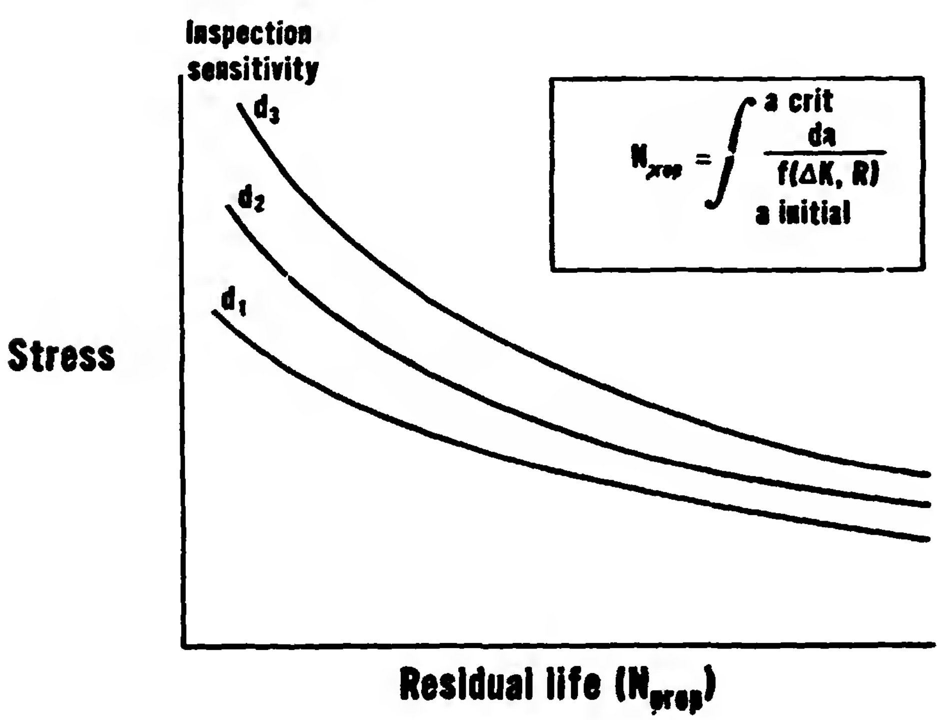


Mag: 11X

ANALYTICAL PROGRAM



FRACTURE MECHANICS LIFE CURVES



FRACTURE MECHANICS LIFE CURVES

Correlation with experience

JT4 steel disk failure predictions

	Disks supplied by suspect vendor		Disks supplied by other vendors	
P/N	Predicted to fail	Failures	Predicted to fail	Failures
360112	2 (1.89)	3	0	0
360113	0	0	0	0
360114	1 (0.284)	0	0	0
405715	0	0	0	0
242915	0	0	0	0

HOT ISOSTATICALLY PRESSED SUPERALLOYS

- Prealloyed powder eliminates segregation
- Powder screening controls defect size
- HIP produces homogeneous structures
- NDE sensitivity greatly enhanced

MATERIAL DEFECTS

Summary

- Smooth section stress limits for current alloys to prevent failures from subsurface defects
- Cleanliness improvements in current alloys through modified processing and controls
- Improved durability thru direct HIP of powder metal superalloys

LOW CYCLE FATIGUE

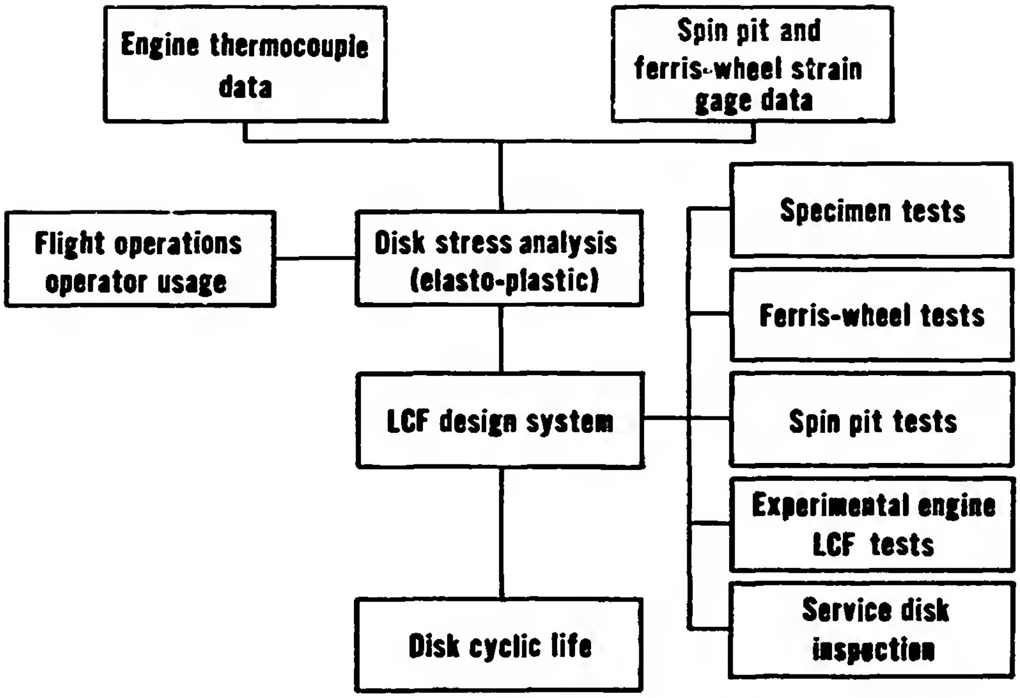
Definition of life

- Number of cycles to 1/32 inch long crack
- Statistical probability of 1 out of 1000

Details of concern

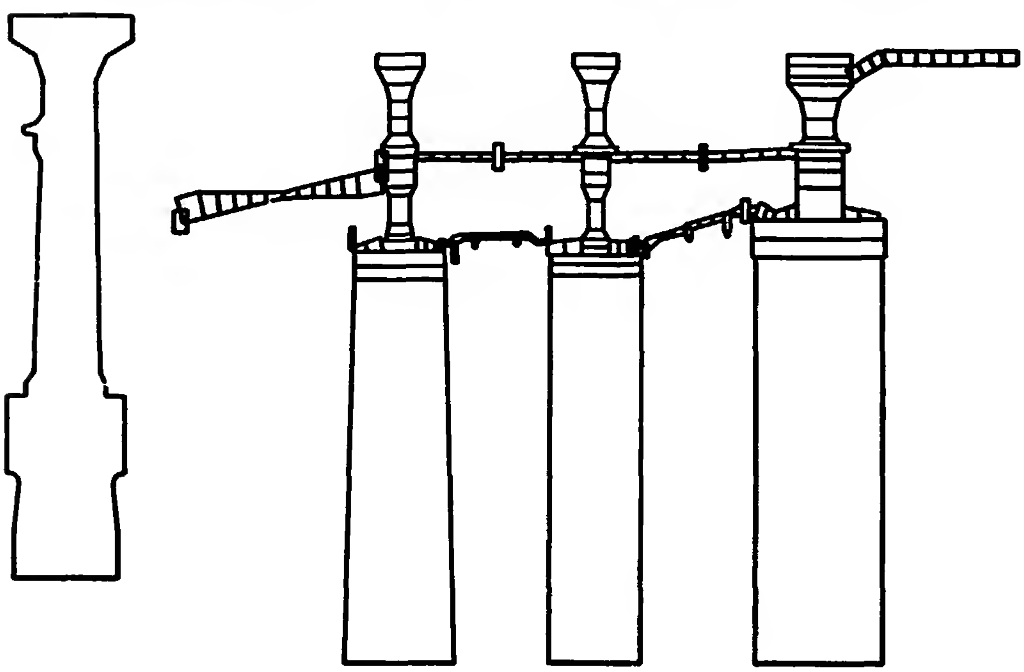
- Smooth disk bores and webs
- Disk bolt holes, flange holes, and rim slots

DISK LCF LIFE DETERMINATION



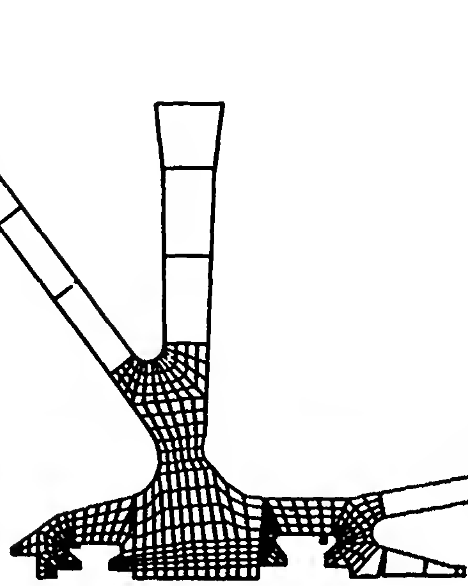
DISK COMPUTER PROGRAMS

- Plastic/elastic disk stress analysis
- Generalized shell analysis



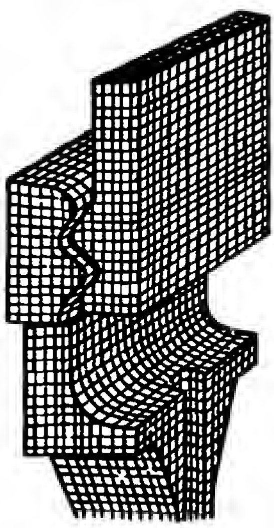
DISK COMPUTER PROGRAMS

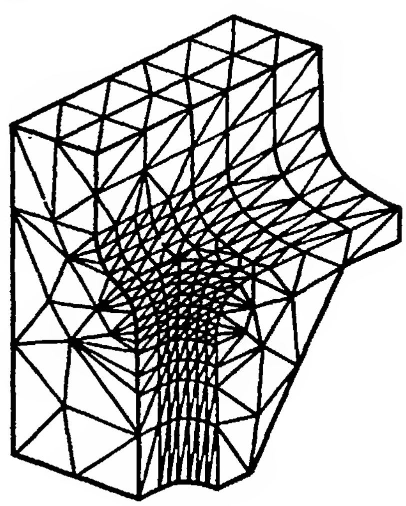
Mixed element F/E code



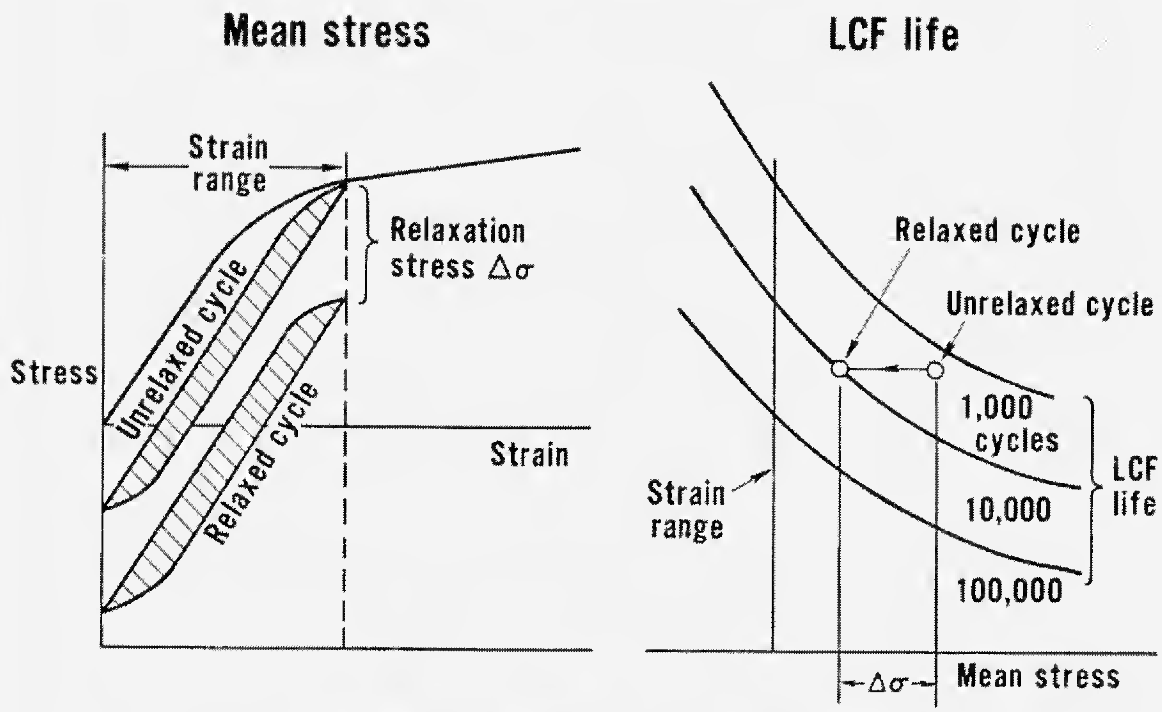
LOCAL STRESS DETERMINATION

- Closed form solution for stress concentration
- 2D and 3D finite element analysis
- 2D and 3D boundary-integral equation techniques

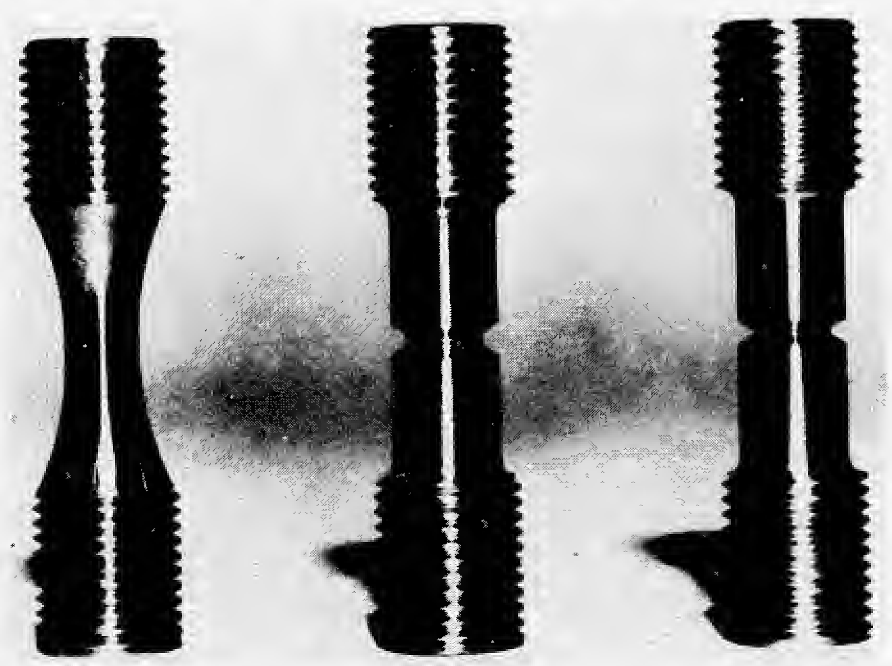




EFFECT OF RELAXATION

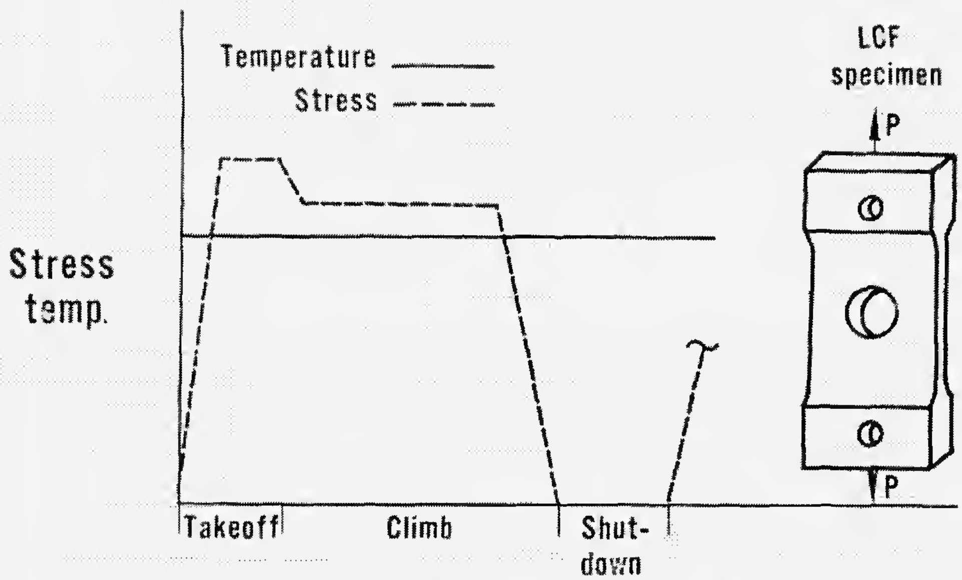


BASIC FORM OF SONNTAG TEST SPECIMENS USED IN LABORATORY EVALUATION OF MATERIAL PROPERTIES



LCF DWELL TEST CYCLE

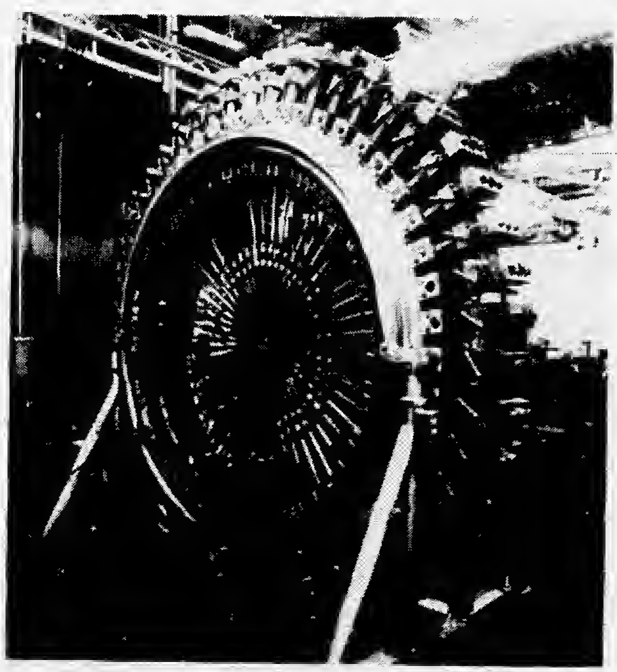
Equivalent to flight cycle



Equivalent testing time

1180 specimens tested

FERRIS-WHEEL TEST RIG FOR HYDRAULIC LOADING OF ROTOR DISKS



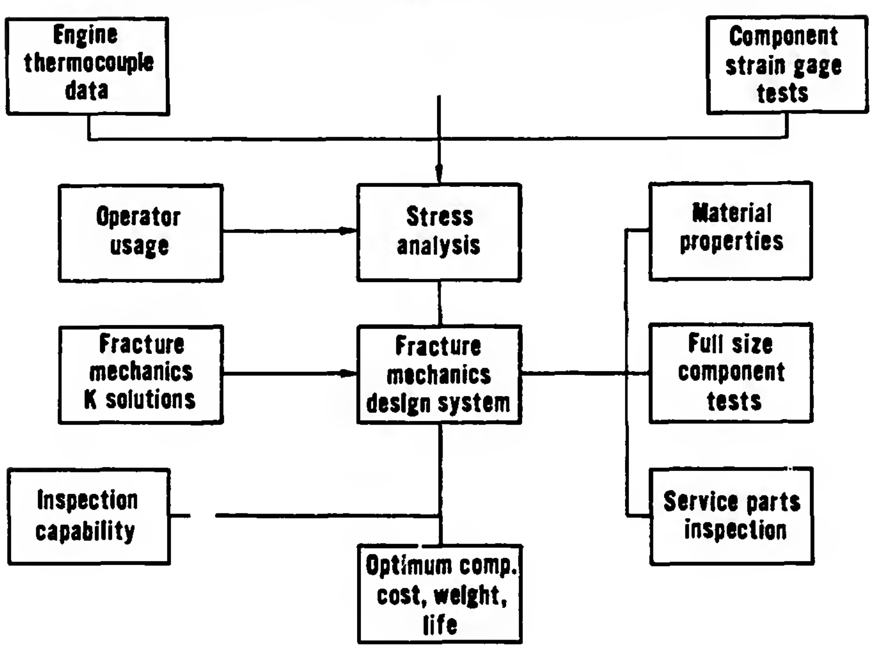
LOW CYCLE FATIGUE –
A CONTINUING INVESTIGATION

New alloy characterization
- High creep strength titaniums
- Powder metal superalloys

Quality considerations
- Material variability
- Surface finish preparation
- Coatings
- Surface integrity

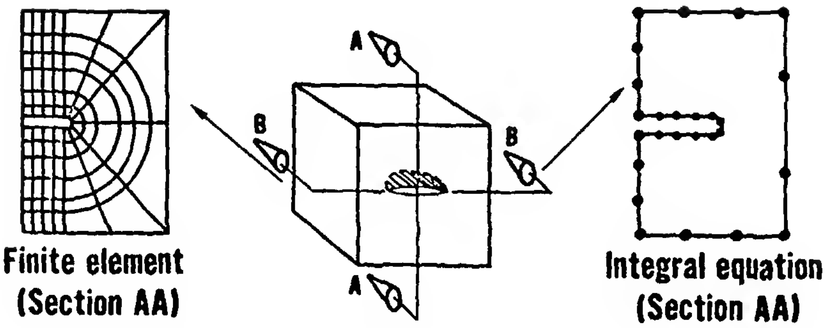
Basic fatigue studies
- Cumulative damage
- Multi-axial fatigue
- Creep -fatigue interaction
- Fatigue mechanisms

FRACTURE MECHANICS DESIGN SYSTEM



ΔK CALCULATION METHODS

- Numerical procedures



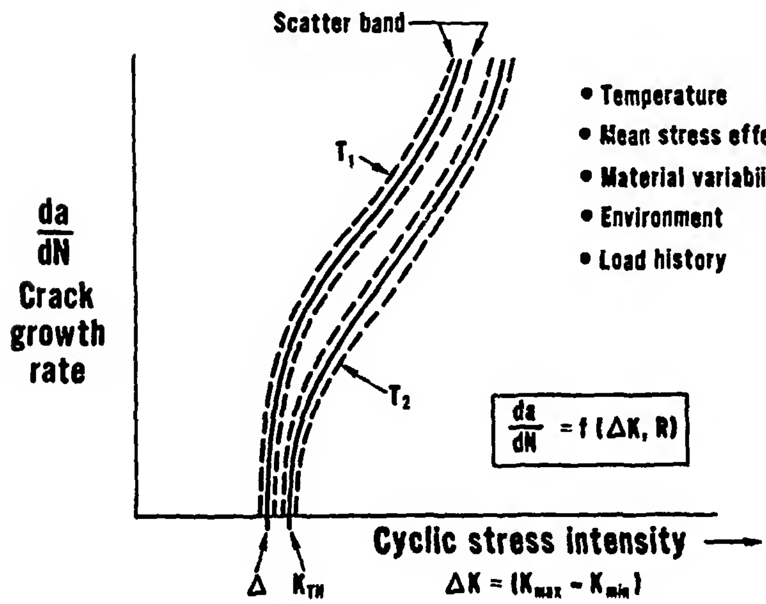
Finite element (Section AA)

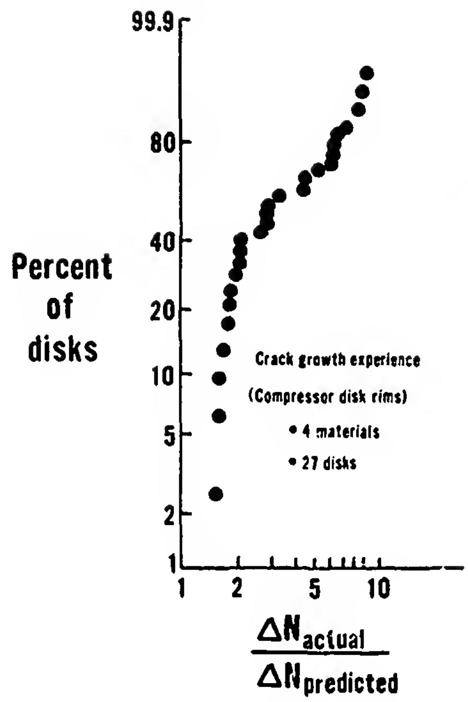
Integral equation (Section AA)

- Influence function method

$$K_j = \int_S h_j\,(X_i,\ \text{geometry})\ \sigma(X_i)\, dS$$

MATERIAL DATA BASE





FRACTURE MECHANICS

Calibration

- Residual life predictions calibrated against crack behavior in specimens and components
  - Smooth sections
  - Bolt holes
  - Rim slots

LOW CYCLE FATIGUE/FRACTURE MECHANICS

Summary

- Well calibrated design procedures minimize low cycle fatigue cracking
- Fracture mechanics considerations assure crack tolerant designs and material selections
- No uncontained disk failures due to LCF in P&WA parts shipped since 1965

DISCUSSION

H. Rubel, Lockheed-Ga.

You have confirmed the SAE findings that progress has been made on low cycle fatigue, and I hope that this effort will be continued. I am concerned about HCF and flutter.

The airplane manufacturer, as we discussed earlier, must show that when certain things go wrong, the system still is operable. I am thinking along these same lines for engines. In a turbine, clogging of the nozzles may occur, which could excite a resonance in the running range, and could lead to failure. As another example, stator vanes in the rear end of the compressor could have its incidence angle changed due to attachment loosening and hence drive a particular disk to flutter. Would it be desirable to put some effort along those lines to ascertain margins for various deteriorated engine parts? In this way the airframe manufacturer and the user could know what degrees of safety exist in particular cases. A small incidence change may be more critical in some stages than in others. Should we not look at old cracked parts as well as virgin parts as is done for LCF? Could we advise the airlines which stages are most critical so that disk rim failures could be minimized?

J.T. Hill, PWA

In the course of an engine development program, extensive compressor and turbine rig testing is conducted at both design and off-design operating conditions. This testing establishes the success of the design effort by mapping the location of both positive and negative flutter boundaries and monitoring the level of resonance stage stress at all intermediate operating conditions. Modifications to the stator geometry, to improve component efficiency, are normally a part of the development effort. The sensitivity of dynamic stage response to such variations are routinely monitored.

As we are well aware, despite our best attempts to identify and solve vibration problems during the development program, HCF remains the major cause of uncontained disk failures. A review of PWA service experience, however, indicates that gas path blockages are not the major cause of such incidents. The presentation indicated that there is a resonant stress prediction system under development at PWA. When developed it will be possible to simulate blockages upstream or downstream of a particular stage, establish the resultant distortion pattern, and the effect on stage resonant stress. Such an analysis program, when developed, will permit the designer to assess the sensitivity of a particular design to the limits of gas path deterioration.

G.L. Gunstone, CAA-UK

I think we all started out worrying mostly about LCF and I think because we have done a very good job on that we nearly have it solved. High cycle fatigue is now the next major problem.

We are proposing to introduce a recommendation in our requirements which is being prepared right now, and it will read something like this. The blades should be designed in this order of strength from weakest to strongest: the airfoil, the blade root, the disk root, and the disk rim. Hence, any high cycle

effect is more likely to bring out a blade than break the disc. I'd be interested to know if anybody has any comments on that.

G.J. Mangano, NAPTC

That particular matter is scheduled to be discussed tomorrow. Thank you.